STATISTICAL DELAY TIMES IN SMALL GAS SPARK GAPS*

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Summary

Statistical times were measured as a function of overvoltage and gap age in small (0.127 mm), flowing-gas spark gaps. Air, nitrogen, oxygen and helium are reported on here. Statistical time was determined by averaging 60 measurements of the time between application of voltage to the gap and breakdown. These times, ranging from 100 ns to over 100 μs were measured with 10 ns resolution. Aging was done by breaking down the spark gap 40 times per second until the desired number of pulses were obtained (5000, 50,000, 500,000). Aging increased the breakdown voltage of gaps filled with air, nitrogen and oxygen, but had little effect when helium was used. The functional dependence of the statistical time on electric field strength was not changed by aging. Limited results showed statistical time increasing with pressure in air-filled spark gaps.

Introduction

The time between application of an overvoltage to a spark gap and the collapse of voltage across the gap can be divided into two periods (See Figure 1).

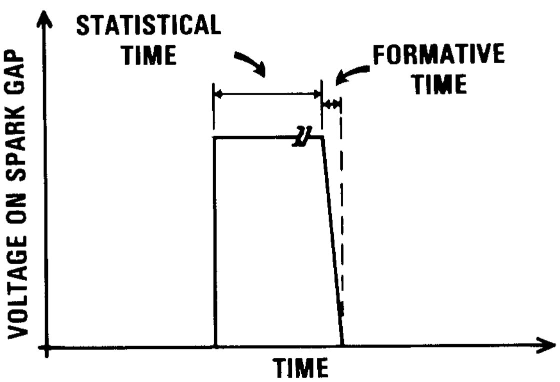

Figure 1. Definition of statistical and formative times.

The first, from the time voltage is applied until the voltage begins to fall, is the time-to-breakdown. A more useful number is the statistical time which is the mean of the distribution of the times-to-breakdown. The second period is the formative time during which the current rapidly rises until limited by the external circuit. We have reported our measurements of the change in resistance of the gap R(t) during the formative time and the effects of statistical time on those measurements.[1, 2, 3] In the experiments reported here, the formative time is very short compared to 100 ns; we therefore do not consider it in the analysis of the present data. Practically, the effect of statistical time is jitter in spark gap firing, but it also provides insight into what occurs in the gap before large currents flow. The minimum time-to-breakdown and the form of the distribution of times-to-breakdown provide checks of the models of events leading to breakdown.

The Apparatus

Figure 2 shows the experimental set up.

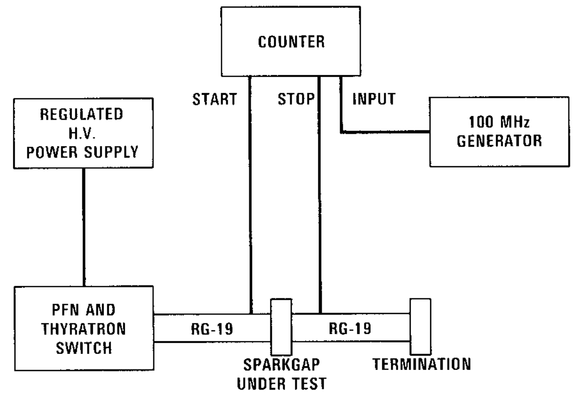

Figure 2. Block diagram of experiment.

A capacitor, charged from a regulated power supply, was discharged by a hydrogen thyratron to create a voltage pulse on the RG-19 coaxial cable. The arrival of the leading edge of the voltage pulse at the spark gap was sensed by a capacitive voltage divider and used to start a digital counter. When the spark gap broke down, a second capacitive voltage divider detected the voltage to the right of the gap and produced a signal which stopped the counter. The signal being counted was a 100 MHz time mark generator so each count represented 10 ns. A matched load terminated the coaxial cable and absorbed the voltage pulse. The duration of the voltage pulse applied to the coaxial cable was determined by the discharge time of the capacitor originally charged from the high voltage supply. The capacitor and discharge circuit were designed so the voltage applied to the coaxial line would droop less than 5% in 100 μs. The fall time of the thyratron anode voltage, the time constant of the capacitive voltage dividers, and the frequency response of the signal handling circuit limited the minimum time the system could accurately measure to between 50 and 100 ns.

Flowing gas was used in the spark gap to sweep away any debris from the previous breakdown. Gas enters from one side of the gap, flows across the gap, and leaves through a channel in the dielectric on the other side of the gap. More than six times the amount of gas in the spark gap moves through the gap between successive breakdowns even at the highest repetition rate used for aging. The exact flow patterns are not known however, and mixing may not be complete. Typical waveforms observed with a Tektronix 6015 high voltage probe at the input to the transmission line are shown in Figure 3. The first, Figure 3a, shows the negative voltage pulse applied to the line and, since breakdown did not occur, how the voltage level was held on the line. The slight droop is the 5% per 100 μs decay mentioned above.

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14. ABSTRACT

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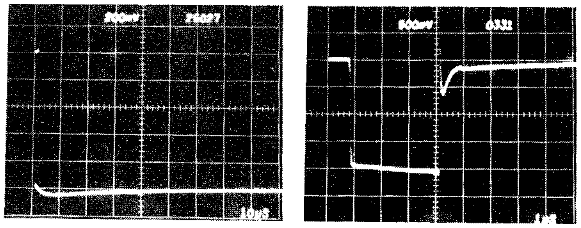

Figure 3. Waveforms of voltage across spark gap.

The readout in the upper right is time-to-breakdown. Because breakdown did not occur, the counter registers 250 μs (25027 x 10 ns) as explained below. Figure 3b shows the voltage on the transmission line when breakdown occurs. In this case the length of the negative pulse was the time-to-breakdown, correspondingly the counter reads 3.3 μs.

The transmission line spark gap is shown in Figure 4.

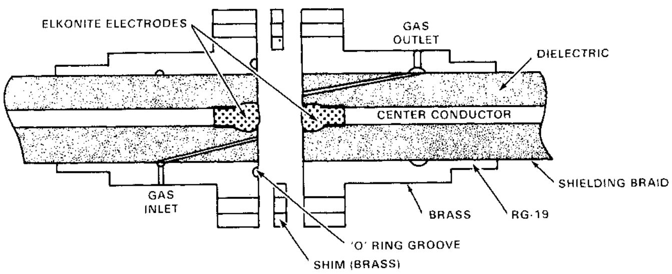

Figure 4. Section of spark gap.

The RG-19 cable geometry was preserved as much as possible in the gap so that when breakdown occurred, the impedance of the cable would be nearly continuous. Elkonite electrodes were installed to minimize wear and assure that the gap spacing did not change during the experiment. The brass flanges surrounding the spark gap continued the outer conductor across the gap, provided channels for gas flow and housed the capacitive voltage dividers on either side of the spark gap. The gap length was set by the size shim installed between the flanges. For the work reported here, a 0.127 mm (5 mil) gap was used. The Elkonite electrodes were ground flush with the end of the coaxial cable and the brass flanges and then the electrode edge was rounded to diminish electric field enhancement. The electrodes showed a nearly even distribution of spark sites after the tests.

Procedure

Before each series of tests, the spark gap was disassembled, refinished and cleaned. Refinishing was done by polishing the center electrode until all traces of previous arcs had been removed. Since the electrodes are Elkonite and only about 20 mJ are discharged through each spark, very little polishing was required. The amount of polishing required is important because the electrode face must remain flush with the end of the coaxial cable. The entire gap was then cleaned with a Freon degreaser and acetone and air dried. After assembly, the selected gas was passed through the gap for 10 minutes before the experiment was started.

The gases used in these experiments were commercial grade. Gas pressure was measured at the inlet port on the spark gap, and gas flow (corrected for gas density) at the outlet port. A gas pressure regulator at the gap held pressure and flow constant during the test. Gap length was set during assembly of the gap by installing a shim between the flanges on the spark gap. The gap length could be checked by measuring the capacitance seen from the terminated-end of the coaxial line with the input end shorted. The gap capacitance was only about 5% of the cable capacitance, so this was not a precise way of measuring the gap length, but it did provide a convenient monitor for gap length changes during the test runs.

The time mark generator was checked against a second calibrated source at least twice a day when data were being collected. The functioning of the start/stop circuitry was checked by comparing the counter readings with oscilloscope photographs. This was done at the beginning of a run and at least once in every 60 data points, but no errors were ever detected.

High voltage power was supplied by a Kilovolt Corporation Model KVR24-500S 24 kW regulated power supply. Less than 10 watts were required even when the gap was being fired at a 40 Hz rate. Thus the power supply easily provided the current necessary to recharge the circuit to the set voltage after each breakdown. The voltage applied to the spark gap was measured at the input to the transmission line. Two ways of applying a voltage pulse to the transmission line and spark gap were available. During aging, voltage pulses were applied to the gap at a 40 Hz rate When data were being collected, a manually operated single shot circuit applied single pulses. The time between breakdowns during data runs was 5 to 10 seconds. Occasionally the gap did not break down during the voltage pulse. In this case, the counting circuits automatically reset after 250 μs, and breakdown was assumed to have occurred at 250 μs. This treatment set the maximum value the time-to-breakdown could have and hence lowered the mean. Statistical time was calculated by simply finding the arithmetic mean of 60 recorded times-to-breakdown. The order in which parameters were changed was constant. First, electric field was changed so its effect on statistical time could be seen. Second, the gap was aged at a rate of 40 sparks per second. And finally, the gas pressure in the gap was varied.

Results

Figures 5, 6, 7 and 8 show the strong dependence of statistical time on the electric field, and how this dependence is affected by spark gap aging with various gases. For a given electric field the statistical time increases with aging in air, oxygen and nitrogen but is little changed when helium is used. Another way of saying this is that the breakdown field increases (for a given statistical time) with aging in all the gases used except helium. Chemical changes at the surface of the electrodes apparently cause most of the aging effects seen. Although the present data shows a greater aging effect in oxygen-filled spark gaps than in those filled with nitrogen or air, the differences are less than the experiment could accurately determine. Further measurements are needed to determine detailed aging rates.

The graph showing aging with nitrogen (Figure 7) also dramatically illustrates the dangers of using small samples (in this case only 60) when the actual distribution of values is very broad.

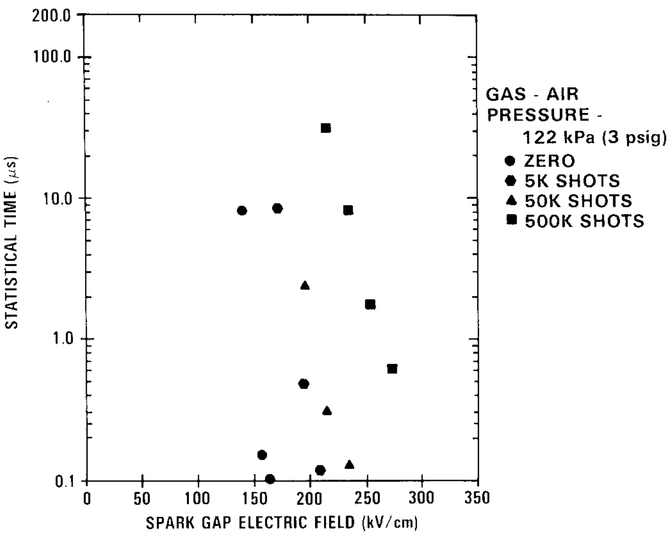

Figure 5. Aging in air.

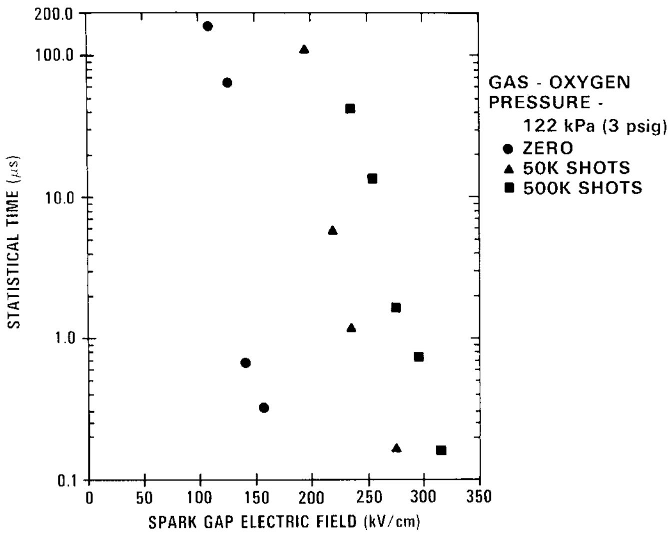

Figure 6. Aging in oxygen.

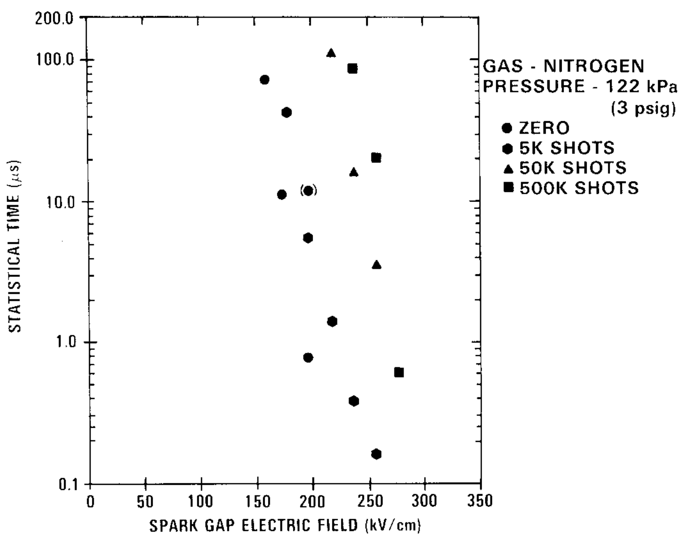

Figure 7. Aging in nitrogen.

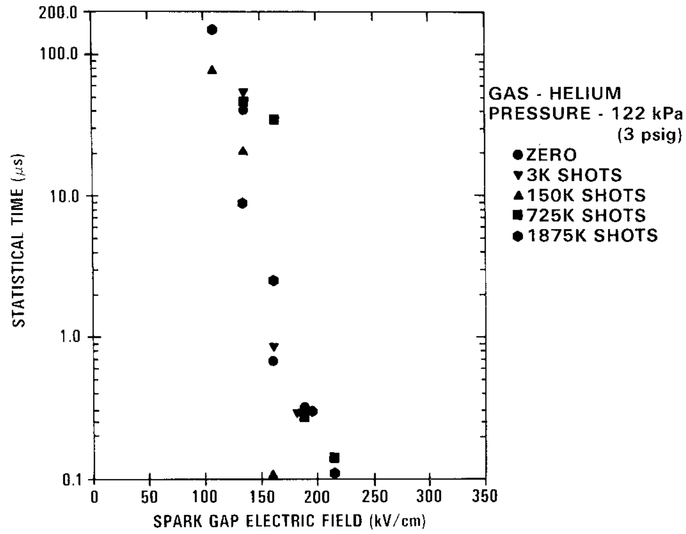

Figure 8. Aging in helium.

As noted above, occasionally the spark gap did not break down when the voltage pulse was applied to it, and in these cases the time-to-breakdown was recorded as 250 μs. The solid circles plotted on Figure 7 show two points for an electric field of 195 kV/cm. The data taken at 195 kV/cm are 60 values that average 0.79 μs and 3 non-breakdowns. If the 3 non-breakdowns are treated as 250 μs data, the mean moves to 12.18 μs shown as a point in parentheses. The deviation of this point from the trend of the other data is most likely a reflection of the broad distribution of the times-to-breakdown.

Figure 9 compares the breakdown characteristics of gaps filled with air, oxygen, nitrogen and helium.

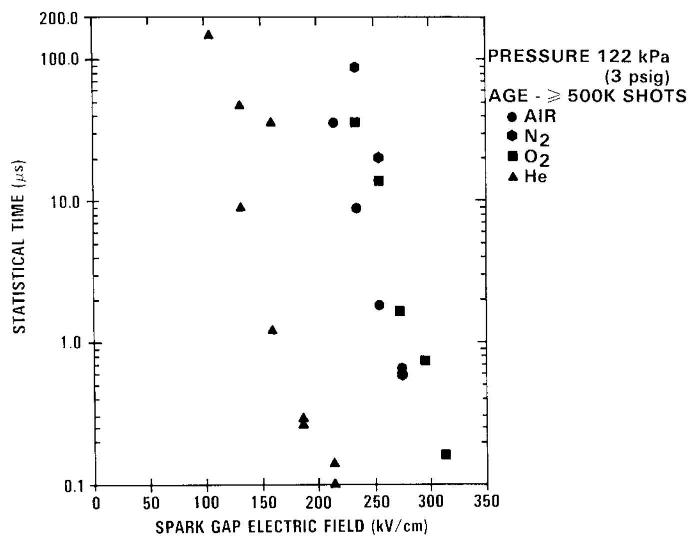

Figure 9. Comparison of several gases.

The data shown was collected after the spark gap had been aged with at least 500,000 shots in the gas used. The values for air, oxygen and nitrogen are close to each other and significantly above the values for helium. These are the same relationships that exist in the more common measurements of static breakdown field. The points follow roughly a straight line on the semilog plot, but have too much variation to draw any detailed quantitative conclusions.

The difficulty is that too few points were used in finding the mean of a distribution that is very broad.

Gas pressure effects were investigated briefly and are shown in Figure 10.

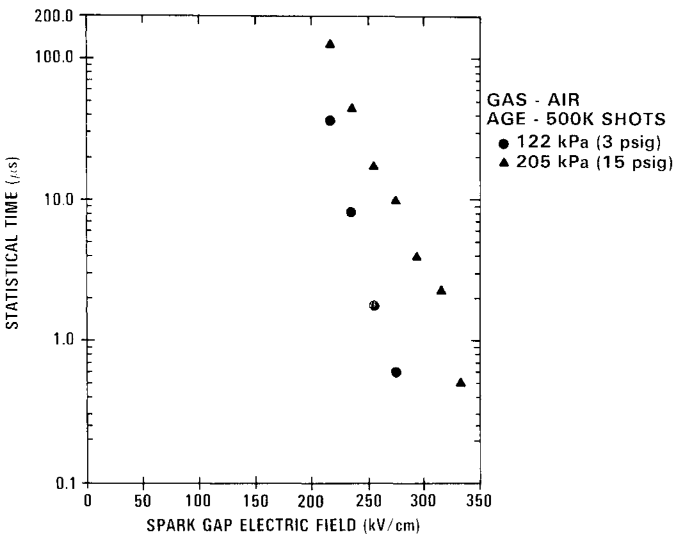

Figure 10. Change in statistical time with gas pressure.

Increasing pressure increases the statistical time in air. This is expected since, for a given electric field, the overvoltage at the lower pressure is greater than the overvoltage at the higher pressure.

Discussion

The distribution of times-to-breakdown has been shown to have an exponential (Laue) distribution when statistical times are less than tens of ns.[4] The distribution seen here, with much greater statistical times (1-10 μs), is very broad as is an exponential, but does not always fit the exponential well. Its exact character remains to be determined. Statistical time is strongly effected by the electric field. Changes in electric field of 50% to 100% send the statistical time flying over three orders of magnitude. The present work does not show various gases greatly affecting the rate of change of statistical time with electric field. This would be expected if the emission rate of electrons from the cathode determines the start of breakdown. The relative breakdown strengths of gases does not change as a function of statistical time, also the effects of pressure are at least similar as statistical time changes.

One of the most striking features of the data presented here is the very high electric fields required to cause the breakdowns studies. A number most people remember is that air breaks down at 30 kV/cm. Compare this to the 150 to 300 kV/cm measured here. The enormous difference can be understood by considering two factors: gap length and statistical time. It is well known that the field needed to break down a spark gap is inversely proportional to the gap length.[5] While 30 kV/cm will cause breakdown of a 1 cm air gap, about 62 kV/cm is required when the gap length is reduced to 0.127 mm (the gap length used in this work). The effect of the statistical time can be seen by fitting an exponential curve to the data shown in Figure 5 for an aged, air-filled spark gap. Extrapolating from statistical times of tens and hundreds of microseconds in the present data to one or two seconds yields estimated breakdown fields of 66 kV/cm and 56 kV/cm respectively. This is surprisingly close to the 62 kV/cm considering that the extrapolation was over several orders of magnitude.

References

1. W. K. Cary, Jr., J. A. Mazzie, IEEE Trans. Electron Devices, ED-26, 1422, 1979

2. W. K. Cary, Jr., D. D. Lindberg, J. W. Rice, IEEE Second International Pulsed Power Conference, Digest of Papers, p. 114, 1979

3. D. D. Lindberg, R. J. Gripshover, J. W. Rice, IEEE Fourteenth Modulator Symposium, Orlando, Fla., June 1980

4. P. Felsenthal, J. M. Proud, Phys. Rev., 139, pg A1976, 1965

5. J. J. Thomson, G. P. Thomson, Conduction of Electricity through Gases, Volume 2, Dover Publ., 1969, (reprint of 1933 edition)